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MEASUREMENT OF FREE WATER IN CLOUD UNDER CONDITIONS OF ICING

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ADVANCE RESTRICTED REPORT

MEASUREMENT OF FREE WATER IN CLOUD UNDER CONDITIONS OF ICING

By J. K. Hardy*

SUMMARY

Measurements have been made, in flight, of the concentration of free water present in clouds under conditions of icing. These show the beneficial effect of kinetic heating in reducing the severity of those conditions, and permit the functioning of the thermal system for protecting airplanes against ice to be analyzed.

The concentration of free water is deduced from measurements of the humidity of the air after the water had been vaporized.

INTRODUCTION

A defect in all the tests of the protective equipment of airplanes under conditions of icing, so far reported, is that the physical characteristics of the conditions of icing have not been specified. In the case of the thermal system of protection, this defect has retarded development, since it has not been possible to analyze the performance of the system under conditions of icing. The defect has been remedied, in part at least, in tests in icing conditions of a C-46 airplane which had been equipped by the Ames Aeronautical Laboratory with a thermal ice-prevention system (reference 1).

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*This report was prepared by Mr. Hardy in collaboration with the staff of the Ames Laboratory during a period of active participation by Mr. Hardy in the NACA icing research program.

The physical conditions of icing are specified by the temperature of the air, the concentration of free water, and the size of droplet present in the cloud. The measurements, which have been made in the C-46 airplane serve to determine both temperature and the concentration of free water. The size of drop has not been measured, but this appears to be of secondary importance.

The concentration of free water was determined indirectly, by measuring the temperature of the dew point of the air after the free water had been vaporized, and by taking such other measurements as served to determine the static temperature of the air prior to heating. In the absence of special apparatus, it was necessary to use air from the main duct of the thermal system. The objection to this was realized fully: namely, that the concentration of free water might be affected seriously by deflection of the droplets before vaporization. Vaporization occurs in the main exchanger on the exhaust of the engine. It was thought, however, that the measurements would be valuable in giving a comparative measure of the severity of the conditions of icing. There is, in fact, evidence to show that the concentration of free water, present in the air before disturbance, is given with much greater accuracy than was anticipated.

The measurement of the concentration of free water is the subject of the present report. The analysis of the performance of the thermal system of protection, made possible by these measurements, is the subject of a separate report (reference 2). Details of most of the flights referred to by numbers in this report will be found in reference 3. The measurements were made in the vicinity of Minneapolis, Minn.

METHOD OF MEASUREMENT

Humidity

The humidity of the air in the main duct was measured. This duct carries air, at a temperature of about 350° F, from the heat exchangers on the inboard side of the engines to the empennage. A sample of the air is taken through a 3/8-inch-diameter metal tube to a dew-point instrument. The tube, which is about 6 feet long, is at a temperature some 20° F above that of a highest recorded temperature of the dew point so that there is no risk that water was condensed.

The dew-point instrument is of the automatic type described in reference 4. As an automatic instrument it had defects. It was used practically as a hand-operated instrument by setting the grid bias to give an oscillation in temperature of the mirror of 1° F, or so, above that of the dew point. The temperature of the mirror, as registered by a thermocouple soldered to the surface, was measured in terms of the deflection of a millivoltmeter. The cold junction of the thermocouple was immersed in a mixture of ice and water.

Air Temperature

The temperature of the air outside the cabin was measured by a mercury-in-glass thermometer. This is mounted outside the window next the dew-point instrument 6 inches from the side of the fuselage. The stem is mounted fore or aft, and the bulb, at the downstream end, has a double concentric screen against solar radiation consisting of tubes 7/8 inch and 9/16 inch in diameter, 3 inches long. The outer tube is extended so as to support the stem of the thermometer. The ends of both tubes are open. The mounting is shown in figure 1.

Procedure

The procedure adopted was as follows: The mirror of the dew-point instrument was cleaned, with the bias set to give full heat. The bias was then reduced slowly until the condition, already mentioned, of slight instability about the temperature of the dew point was obtained. This was checked by lifting the lid just enough to observe the mirror. The temperature of the mirror was then recorded and, as quickly as possible, the temperature of the outside air, height, and airspeed were recorded in this sequence. The bias would be trimmed as required to suit change in dew point. The cleaning of the mirror was repeated only as was necessary.

METHOD OF CALCULATION

Concentration of Water

If the aqueous vapor pressure in the air is known, both in the undisturbed state e_0 with free water present, and in the duct e_1 when the free water has been vaporized, the amount of free water is given by the equation

$$n = 0.622 \frac{e_1 - e_0}{p} \tag{1}$$

where p is the local barometric pressure, and n is given in mass of water per unit mass of air in any units. The quantity which is significant in determining the rate of precipitation of water on parts of an airplane is the weight of free water per unit volume of air. This quantity, in grams per cubic meter, is given by the equation

$$m = 1215 \; n \frac{\rho}{\rho_0} \tag{2}$$

in which ρ/ρ_0 is the density of the air, locally, relative to that at standard temperature and pressure (59° F, 29.92 in. Hg). These equations are derived from the "gas equation"; derivation is given in the standard textbooks.

The value of e_1 is the vapor pressure, at saturation, at the temperature of the dew point of the air in the duct. The values given in the Smithsonian Physical Tables (1934 edition) have been used for all the calculations.

The value of e_0, the vapor pressure of the air in the cloud in the undisturbed state, cannot be measured direct. A sample of air, at rest relative to the airplane, has been subjected to kinetic heating, in which process water, in considerable quantity, passes from the liquid to the vapor phase; this may be seen from the example given later. It must be presumed, therefore, that the air in the cloud is saturated. The possible departure from this condition, either in the direction of supersaturation by reason of the smallness of the drops, or unsaturation from dissolved substances, is relatively small. The real uncertainty is the true static temperature of the air.

Static Temperature of Air

The rise in temperature from kinetic heating has been calculated, on the assumption that full saturation is maintained whenever there is sufficient free water to fulfill this condition (i.e., whenever the temperature of dew point of the hot air in the duct exceeds that registered by the thermometer outside the fuselage). In this case, the theoretical rise in temperature for wet air, in degrees Fahrenheit, is

$$\Delta t = 1.77 \frac{c_p}{c_{p_w}} \left(\frac{V}{100}\right)^2 \tag{3}$$

V is the true speed in miles per hour, and c_p and c_{p_w} are specific heats of dry air and wet air, respectively. The value of c_{p_w} is taken from the table in reference 5.

In cases when there is insufficient water for saturation to be maintained and the vapor becomes superheated, the correct value of Δt could be found by trial and error. The procedure adopted has been to calculate the values of Δt both for dry and for wet air, and to proportion the difference in terms of the temperature of the dew point thus,

$$\Delta t = \Delta t_w + (\Delta t_c - \Delta t_w) \frac{t_a - t_d}{\Delta t}$$

where

t_a the temperature of the air observed

t_d the temperature of the dew point

Δt_w the effective temperature rise for wet air

Δt_c the effective temperature rise for clear air

The value of Δt on the right side of the equation is estimated. The method is approximate but sufficiently accurate.

The value of Δt in clear air, in degrees Fahrenheit, is

$$\Delta t = 1.77 \left(\frac{V}{100}\right)^2 \tag{4}$$

The value of Δt given by equations (3) and (4) is the theoretical value. That recorded by a thermometer is some fraction of this value. Tests in clear air show that, on the C-46 airplane, the effective value of Δt for the thermometer is $0.8\Delta t$ theoretical. In conditions of icing, it has to be assumed that this value holds, even when there is a large piece of ice on the forward end of the thermometer tube such as collects after prolonged flight.

Example

The method of calculation will be illustrated by an example from observations taken on flight 65, run 1. The following were observed:

Temperature of dew point, 30.3° F

Temperature of air, 27.1° F

Indicated airspeed, 170 miles per hour

Pressure altitude, 3900 feet (660 mm Hg)

From these observations

$$\frac{\rho}{\rho_o} = 0.93$$

and

true speed = 177 miles per hour

From equation (3)

$$\Delta t = 1.77 \times \frac{0.24}{0.361} \times \left(\frac{177}{100}\right)^2 = 3.7^\circ \text{ F}$$

Effective $\Delta t = 3.7 \times 0.8 = 2.9^\circ$ F

Static air temperature = 27.1 − 2.9 = 24.2° F

Vapor pressure (saturated) at 24.2° F

(e_o) = 3.31 millimeters of mercury

Vapor pressure (saturated) at 30.3° F

(e_1) = 4.27 millimeters of mercury

From which

$$(e_1-e_0) = 0.96 \text{ millimeter of mercury}$$

From equation (1)

$$n = 0.622 \times \frac{0.96}{660} = 0.00091 \text{ gram per gram}$$

and from (2)

$$m = 1.03 \text{ grams per cubic meter}$$

As a matter of interest, the amount of water evaporated by kinetic heating will be calculated. The theoretical value of Δt, 3.7° F in this example, will occur on the leading edge of the wing and other parts of the airplane. The kinetic temperature of those parts will be 27.9° F and vapor pressure 3.86 millimeters of mercury. The increase in vapor pressure, from that at static air temperature, is 0.55 millimeter of mercury which corresponds to the evaporation of 0.59 gram of water per cubic meter of air. The amount decreases with temperature in proportion to the decrease in saturated vapor pressure with temperature.

RESULTS

A selection from the considerable number of observations has been made primarily with a view of showing the conditions in which tests of the thermal system of the C-46 airplane were conducted, and when possible, the constancy or otherwise of these conditions. The results are given in table I. Included in this table are the temperatures of the surface of the wing measured at the leading edge of station 159 for convenience of reference in the report on the analysis of the thermal system of the C-46 (reference 2). These temperatures were taken with a surface-type thermocouple.

The results of measurements, from ground level up through a layer of cloud, are shown graphically on a pseudo-adiabatic diagram in figure 2.

DISCUSSION

The value of concentration of free water in the table is given to the nearest hundredth of a gram per cubic meter. This precision is quite unwarranted by the accuracy of the method of measurement, but it shows the steadiness of conditions during a particular run, and is valuable, in certain circumstances, in demonstrating the effect of a small change in conditions.

Measurement of Dew Point

It is difficult to assess the accuracy with which observations are made in flight. In favorable conditions the dew point could be measured, it is believed, to within $\pm 0.2^{\circ}$ F. The possibility of systematic error, from leakage of exhaust gas into the air in the heat exchanger, was checked from time to time by measuring, in clear air, both the dew point of the hot air in the main duct and that drawn direct from outside the fuselage. The variation was within that normally observed in air drawn from the same source. The most critical observation of this character was a dew point of -41° F at 10,000 feet on flight 60 with air at 13.3° F. This was measured with air drawn from the duct; the change to -43° F on changing to the external tube is insignificant.

Air Temperature

The temperature of the air outside the fuselage was read to $\pm 0.1^{\circ}$ F, but the actual temperature is known with considerably less precision than this would imply. Frosting of the stem of the thermometer was of regular occurrence, and while the bulb could not be seen, it is probable that frost formed also on this. While frost is forming, a temperature above correct will be registered. This is the disadvantage of having open the ends of the tube screening the thermometer. An advantage is that the kinetic temperature rise Δt is definitely that for wet air. With the forward end plugged, the value of Δt will be, presumably, somewhere between the values for wet and for dry air. Exactness in the value of Δt is not so important as might be expected. This has been shown by repeating some of the calculations with Δt as for dry air. In the worst case, where the temperature is high, the value for concentration of free water is increased by 0.2 gram per cubic meter.

In changing conditions, lag in response of the thermometer will cause an error of uncertain magnitude. A thermometer of the resistance or thermocouple type should be used, it is believed, and comparative tests should be made with different types of shield.

Error in Sampling

The magnitude of the error in sampling, produced by deflection of the droplets of water prior to vaporization, has not been determined with certainty. Before reaching the heat exchanger the concentration of free water is decreased slightly by precipitation onto the propeller, is increased by deflection round the cowl of the engine, and is decreased, finally, by deflection at the entry to the heat exchanger. The entry has an area of 0.32 square foot, and the velocity on entry is about one-eighth the velocity of flight.

The error in sampling can be determined by measurement in a cloud of the type which has formed as a result of adiabatic cooling, with no mixing by convectional or other process. In this type of cloud it is possible to predict, from the pseudo-adiabatic diagram, the gradient both of temperature and concentration of free water.

Those conditions were encountered, it appears, immediately after take-off in flight 60. The record is imperfect, as it has been necessary to estimate airspeed and to interpolate the height at which two sets of observations were made. In this, it is assumed that a normal steady climb was made. The results are plotted in figure 2 and are given also in table I.

Starting with the temperature at ground level, observed while taxiing, the temperatures observed in flight are almost exactly those predicted by assuming dry-adiabatic expansion to the base of the cloud and wet-adiabatic through the cloud. The base of the cloud occurs at the point of intersection of the lines of temperature of the air and of the dew point. The agreement between the temperatures predicted and those observed indicates that there is no mixing of the air, either in or below the cloud. In these circumstances, the total water content (i.e., vapor plus free water) should not change with height. The temperature of the dew point, therefore, should follow the line of constant total water on the diagram. In the cloud at 3600 feet, the dew point predicted, from that measured in clear air below the cloud, should be 15.5° F; whereas, it was found by measurement to be 16.2° F. These correspond to concentrations of free water of 0.32 and 0.40 gram per cubic meter, respectively. How much of this difference may be ascribed to errors, both of observation and estimation, and how much to deflection of the droplets, is not known. The agreement is sufficiently close to warrant the conclusion that the concentration of free water, as given in table I, is not greatly above the true value.

Reduction in Severity of Icing by Kinetic Heating

This report would be incomplete without some mention of the response of the heated wing of the airplane to different concentrations of free water, since this illustrates the physical reality of the evaporative effect of kinetic heating. An analysis of the heated wing is the subject of a separate report (reference 2).

The effect of kinetic heating in wet air is discussed in reference 5, principally in terms of the temperature of the surface. The effect in reducing the severity of icing, by evaporation of water before it strikes, receives no emphasis. It was not known how far, in reality, the droplets of water would respond to the rapid change in temperature on approach to the surface, or how far the advantage of evaporation might be nullified by an increase in concentration of water by deflection round the leading-edge sections.

The tests of the C-46 airplane in conditions of icing have shown that the severity of conditions is reduced substantially by the effect of kinetic heating. For instance, on flight 64 with the thermal system in operation, the leading edge of the wing was observed to be quite dry and the temperature of the surface was identical with that in clear air at the same temperature; this with free water from 0.4 to 0.6 gram per cubic meter.

The temperature of the heated surface of the wing is extremely sensitive to the impact of water owing to the cooling effect of evaporation. For instance, with air at 29° F, the temperature of the surface in the vicinity of the leading edge falls from 134° to 81° F, as the surface passes from the condition when no water reaches it to the condition when it is just wet. The quantity of water required just to wet the surface (in addition to that required to saturate the boundary-layer air at the kinetic temperature) is found by calculation to be equivalent to 0.14 gram per cubic meter for 10μ (10^{-5} meter) droplets. The break in temperature is shown by observations on flight 65 (table I). The limit of evaporation by kinetic heating is approached at 2:02 to 2:07 hours, with free water 0.8 gram per cubic meter, and at 3:06 hours the temperature of the surface shows that it is just wetted with free water at 0.96 gram per cubic meter. Theoretically, 0.6 gram per cubic meter should be evaporated by kinetic heating on both of these occasions. The concentration of water at which the surface becomes wet seems to depend upon the size of droplets in the cloud. The size in flights 64 and 65 was estimated to be 5μ to 10μ diameter. In flight 59, when the size was larger, the wing was dry at 0.4 gram per cubic meter and just wet at 0.5 gram per cubic meter. It appears that the larger drops may have broken through to the surface, leaving the air saturated only in part.

Clearly it is impossible to calculate with any certainty the concentration of free water in cloud from the temperature of the surface of a heated body, but it is possible to calculate the rate at which water reaches the surface. This is precisely the information which is required in the design either of thermal or chemical systems for preventing the formation of ice.

The Effect of Depth of Cloud on Severity of Icing

It is common experience to find that the most severe conditions of icing occur just below the top of a cloud. The reason for this is that the concentration of free water increases as the temperature decreases with increase in height. This is shown clearly by the observations taken on flight 60 (fig. 2). The same general effect is shown by those taken on flight 64 (fig. 2). In the latter case, the structure of the cloud is complex, and is not accurately portrayed on a pseudo-adiabatic diagram, as the observations were taken along an oblique path and there is evidence of variation in the composition of the cloud in a horizontal direction.

CONCLUSIONS

The weakness of the method used for determining the concentration of free water in cloud is the uncertainty as to the static temperature of the air in the cloud, and the uncertainty as to the magnitude of the error in sampling. The error in sampling can be reduced to negligible proportions, it is believed, by using a special entry for the air, by mounting this in a position free from disturbance, and by taking in air at the same velocity as that of flight. The determination of the static temperature of the air remains a problem.

The values for the concentration of free water given in this report are believed to be slightly greater than those actually encountered. They are of value principally in that they show the variation in conditions between different tests of the thermal system of protection against ice, and they allow the performance of the system under conditions of icing to be analyzed.

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